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Higgs Production from Gluon Fusion in Warped Extra Dimensions

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Abstract

We present an analysis of the loop-induced couplings of the Higgs boson to the massless gauge fields (gluons and photons) in the warped extra dimension models where all Standard Model fields propagate in the bulk. We show that in such models corrections to the hgg and $h\gamma\gamma$ couplings are potentially very large. These corrections can lead to generically sizable deviations in the production and decay rates of the Higgs boson, even when the new physics states lie beyond the direct reach of the LHC.

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I. INTRODUCTION

Warped extra dimensions, *à la* Randall-Sundrum model (RS) present one of the most elegant solutions to the Standard Model (SM) hierarchy problem [1]. Placing SM fields in the bulk of the extra dimension can simultaneously explain the hierarchies of the SM fermion masses [2–4]. Such models provide a very attractive way to suppress flavor violation by the so called RS Glashow-Iliopoulos-Maiani(GIM) mechanism [2, 5, 6]. The electroweak precision tests put important bounds on the scale of new physics, but by introducing custodial symmetries [7, 8] one can have it around few TeV [7–9].

In this paper, we will analyze the Higgs couplings to massless vector bosons in RS models where all SM fields are in the bulk, and the modification to the hgg and $h\gamma\gamma$ couplings arises from integrating out Kaluza-Klein (KK) partners of the SM fields. Previous works on this topic for RS models have been done in [10–14]¹. These effects were also studied in models of warped extra dimensions in which the Higgs arises as Pseudo-Nambu-Goldstone boson (PNGB) [15] and within the effective theory formalism [16, 17]. The studies of the Higgs production in flat extra dimensions in the models with gauge Higgs unification were carried out in [18]. We will stick to the models with flavor anarchy [5, 6] in which the hierarchies in masses and mixings in the the fermion sector are explained by small overlap integrals between fermion wave functions and the Higgs wave function along the extra dimension. Previous studies of this framework have mainly focused on bounds on the KK scale coming from new flavor violating sources. In spite of the RS-GIM mechanism, it was still found that $\Delta F = 2$ processes mediated by the KK gluon push the mass of the KK excitations to be above ~ 10 TeV [19–21], making them very hard to produce and observe at the LHC [22]. These bounds coming from flavor violation in low energy observables can be relaxed by introducing additional flavor symmetries [20, 23–25], or by promoting the Higgs to be a 5D bulk field (instead of being brane localized) [26, 27]. A similar tension was found in the lepton sector in [28], making scale of $O(5)$ TeV still compatible with experiments. Lower KK scales can be achieved by changing the fermion representations [29] or by introducing flavor symmetries [24]. It is interesting to point out that flavor violating effects can also be mediated by the radion [30], a graviscalar degree of freedom which might be generically the lightest new physics state and therefore may lead to important phenomenological bounds. More recently, it has also been pointed out that models with fermions in the bulk give rise

¹ One of the main differences between our work and previous analysis is that we present analytical results for the contribution of the full KK fermion tower. Other subtle differences are discussed in the main text.

to flavor violation in the couplings of Higgs to SM fermions [31, 32], leading to interesting constraints from $\Delta F = 2$ processes and to flavor violating collider signatures such as $h \rightarrow tc$ (see also the most recent analysis of [12, 33] for further details). Other interesting collider effects like rare top decays $t \rightarrow cZ$ were discussed in [34].

The outline of the paper is as follows: in section II, we consider the effect of just two vector-like heavy fermions, one singlet under $SU(2)_L$ and one doublet. This simple case helps us understand in simple terms the effects caused by the full tower of KK fermions in a realistic 5D setup. In section III we present a calculation of the hgg and $h\gamma\gamma$ couplings for the simple model where all the fermions are in a doublet representation of $SU(2)_L$ or $SU(2)_R$. In this section and in Appendix A we also present a simple way to evaluate the complete KK fermion tower contribution to hgg and $h\gamma\gamma$ couplings. Having explained and derived the new contributions to the Higgs couplings caused by the heavy KK fermions, we proceed in section IV to study quantitatively the main phenomenological effects and outline our conclusions in section V.

II. WARM-UP: NEW VECTOR-LIKE FERMIONS

We begin by computing the new contribution to the hgg coupling using effective theory with just the zero and first KK modes, where we only consider one family of light quarks (say, up and down quarks) augmented by the presence of two heavy vector-like fermions, one in doublet representation of $SU(2)_L$ and the other in singlet representation. This effective theory description has the advantage of being economical and gives lucid physical intuition of the source of new physics contribution. Therefore, we adopt this approach in this section just to illustrate the essential points of our calculation. Moreover, the calculation is more general in the sense that it applies to any Beyond Standard Model (BSM) model in which there exist extra vector-like fermions which mix with SM fermions (see [35] for a similar discussion). The full calculation of the hgg coupling in the 5D warped extra dimension model will be carried out in the next section.

To start, we review here the Higgs boson production through gluon fusion in SM. The coupling between gluon and Higgs mainly comes from top quark loop (See Fig. 1). The partonic cross section for $gg \rightarrow h$ is [36]

$$\sigma_{gg \rightarrow h}^{SM} = \frac{\alpha_s^2 m_h^2}{576\pi} \left| \sum_Q \frac{y_Q}{m_Q} A_{1/2}(\tau_Q) \right|^2 \delta(\hat{s} - m_h^2), \quad (1)$$

where the sum is for all SM fermions, \hat{s} is invariant mass squared of the two incoming

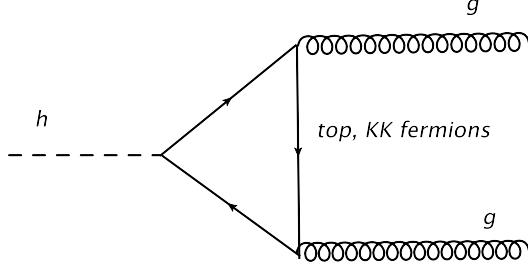


FIG. 1: hgg coupling induced by fermion loop.

gluons, $\tau_Q \equiv m_h^2/4m_Q^2$, y_Q and m_Q are Yukawa couplings and masses of the quarks, and the form factor for fermion in the loop is

$$A_{1/2}(\tau) = \frac{3}{2}[\tau + (\tau - 1)f(\tau)]\tau^{-2}, \quad (2)$$

where

$$f(\tau) = [\arcsin \sqrt{\tau}]^2, \quad (\tau \leq 1); \quad -\frac{1}{4} \left[\ln \left(\frac{1 + \sqrt{1 - \tau^{-1}}}{1 - \sqrt{1 - \tau^{-1}}} \right) - i\pi \right]^2, \quad (\tau > 1). \quad (3)$$

We note that for $\tau_Q \rightarrow 0$ i.e. $m_h \ll m_Q$, the form factor tends to be unity, while for $\tau_Q \rightarrow \infty$ i.e. $m_h \gg m_Q$, the form factor tends to zero. For reference, we consider a Higgs boson with mass 120 GeV, then for c-quark, we have $A_{1/2}(\tau_c) \approx 0.01$; and for a KK fermion with mass 2000 GeV, we have $A_{1/2}(\tau_{kk}) \approx 1.00021$. Therefore, it is a good approximation to treat the form factors for KK fermions as unity, while for light quarks, we can safely ignore their contributions.

In the effective theory with just one KK mode, we have zero mode fermions (q_L, u_R) and first KK fermions ($Q_L^{(1)}, Q_R^{(1)}, U_L^{(1)}, U_R^{(1)}$), where q, Q denote the up-type quark from $SU(2)_L$ doublet, and u, U denote the up-type quark from $SU(2)_L$ singlet. Then we have the following mass matrix:

$$(\bar{q}_L, \bar{Q}_L^{(1)}, \bar{U}_L^{(1)}) \begin{pmatrix} \frac{Y_{q_L u_R} \tilde{v}}{\sqrt{2}} & 0 & \frac{Y_{q_L U_R} \tilde{v}}{\sqrt{2}} \\ \frac{Y_{Q_L u_R} \tilde{v}}{\sqrt{2}} & M_Q & \frac{Y_{Q_L U_R} \tilde{v}}{\sqrt{2}} \\ 0 & \frac{Y_{U_L Q_R} \tilde{v}}{\sqrt{2}} & M_U \end{pmatrix} \begin{pmatrix} u_R \\ Q_R^{(1)} \\ U_R^{(1)} \end{pmatrix} + \text{h.c.} \quad (4)$$

where $Y_{q_L u_R}$ etc. are the Yukawa couplings between the corresponding chiral fermions, and \tilde{v} is the Higgs VEV (note that it is not the same as v_{SM}). The Yukawa couplings matrix is given by

$$(\bar{q}_L, \bar{Q}_L^{(1)}, \bar{U}_L^{(1)}) \begin{pmatrix} \frac{Y_{q_L u_R}}{\sqrt{2}} & 0 & \frac{Y_{q_L U_R}}{\sqrt{2}} \\ \frac{Y_{Q_L u_R}}{\sqrt{2}} & 0 & \frac{Y_{Q_L U_R}}{\sqrt{2}} \\ 0 & \frac{Y_{U_L Q_R}}{\sqrt{2}} & 0 \end{pmatrix} \begin{pmatrix} u_R \\ Q_R^{(1)} \\ U_R^{(1)} \end{pmatrix} h + \text{h.c.} \quad (5)$$

To calculate these fermion contributions to the hgg coupling, we assume that the masses of the KK fermions $\gg m_h$, and therefore their form factors are approximately unity. Before proceeding let us classify different effects contributing to the shift of hgg coupling from that of the SM:

- relation between mass and Yukawa coupling of the lightest state (SM fermion) is modified from the SM value $y_{RS}^{\text{light}} \neq \frac{m_f}{v_{SM}}$;
- we have loop of KK fermion running in the triangle diagrams (see Fig. 1).

So we should calculate

$$\frac{y_{RS}^{\text{light}}}{m^{\text{light}}} A_{1/2}(\tau_{\text{light}}) + \sum_{\text{heavy}} \frac{Y_i}{M_i} = \text{Tr}(\hat{Y} \hat{M}^{-1}) + \frac{y_{RS}^{\text{light}}}{m^{\text{light}}} (A_{1/2}(\tau_{\text{light}}) - 1), \quad (6)$$

where \hat{M} and \hat{Y} are the fermion mass and Yukawa matrices given in Eq. (4) and (5)². The first term on the LHS of the above equation gives the contribution from the SM fermion (lightest mass eigenstate), and the second term comes from the contributions of heavy KK fermions. Note that $\hat{Y} = \frac{\partial \hat{M}}{\partial \tilde{v}}$, therefore, we can use the following trick to calculate the trace [37]:

$$\text{Tr}(\hat{Y} \hat{M}^{-1}) = \text{Tr} \left(\frac{\partial \hat{M}}{\partial \tilde{v}} \hat{M}^{-1} \right) = \frac{\partial \ln \text{Det}(\hat{M})}{\partial \tilde{v}}, \quad (7)$$

we also have

$$\text{Det}(\hat{M}) = Y_{q_L u_R} M_Q M_U \frac{\tilde{v}}{\sqrt{2}} + Y_{Q_L u_R} Y_{U_L Q_R} Y_{q_L U_R} \left(\frac{\tilde{v}}{\sqrt{2}} \right)^3 - Y_{q_L u_R} Y_{Q_L U_R} Y_{U_L Q_R} \left(\frac{\tilde{v}}{\sqrt{2}} \right)^3. \quad (8)$$

Now we expand to first order in $\frac{\tilde{v}^2}{M_Q M_U}$:

$$\text{Tr}(\hat{Y} \hat{M}^{-1}) \approx \frac{1}{\tilde{v}} \left[1 + \left(\frac{Y_{Q_L u_R} Y_{U_L Q_R} Y_{q_L U_R}}{Y_{q_L u_R}} - Y_{Q_L U_R} Y_{U_L Q_R} \right) \frac{\tilde{v}^2}{M_Q M_U} \right]. \quad (9)$$

Note that the masses and Yukawa couplings of the SM fermions are also modified (see [32] for details),

$$\frac{y_{RS}^{\text{light}}}{m^{\text{light}}} \approx \frac{1}{\tilde{v}} \left(1 + \frac{Y_{Q_L u_R} Y_{U_L Q_R} Y_{q_L U_R}}{Y_{q_L u_R}} \frac{\tilde{v}^2}{M_Q M_U} \right), \quad (10)$$

² Note that the real part of the Yukawa coupling will lead to the operator $hG_{\mu\nu}G^{\mu\nu}$, and the imaginary part will lead to the operator $hG_{\mu\nu}\tilde{G}^{\mu\nu}$. For simplicity in this paper we everywhere will assume that we have only $hG_{\mu\nu}G^{\mu\nu}$ operator.

where the last expression was derived using the following assumption ($Y_{q_L u_R} \ll Y_{q_L U_R}, Y_{Q_L u_R} \ll Y_{Q_L U_R}$). This assumption is true for the quarks of the first two generations, and the extra contribution which is important for the quarks of the third generation will be presented in the next section. Now Eq. (6) reduces to

$$\frac{y_{RS}^{\text{light}}}{m^{\text{light}}} A_{1/2}(\tau_{\text{light}}) - \tilde{v} \frac{Y_{Q_L U_R} Y_{U_L Q_R}}{M_Q M_U}. \quad (11)$$

We can see that for the light generation quarks, $A_{1/2}(\tau_{\text{light}}) \approx 0$, we get $-\frac{1}{\tilde{v}} Y_{Q_L U_R} Y_{U_L Q_R} \frac{\tilde{v}^2}{M_Q M_U}$, which is just the contribution coming from the KK modes. Note that this contribution is proportional to $Y_{Q_L U_R} Y_{U_L Q_R}$, which is the product of Yukawa couplings of the KK fermions of opposite chiralities, this structure of the contribution will become essential in calculating the effects in realistic warped model in the next section. It is interesting to see that even though the light SM quarks give negligible contribution to hgg coupling, their KK partners can give sizable new contributions. In addition, there would be an multiplicity enhancement of these KK contributions due to the number of flavors.

The analysis above showed that additional vector-like fermions which mix with SM fermions can alter the hgg coupling significantly. In warped extra dimension models with 5D fermions propagating in the bulk, these extra vector-like fermions naturally come up as the KK towers of fermions. Therefore, we expect generically sizable new physics contributions to hgg coupling in this class of models. We carry out the detailed calculations in warped extra dimension in the next section.

III. MINIMAL WARPED EXTRA DIMENSION MODEL WITH CUSTODIAL PROTECTION

In this section, we first calculate the KK fermion contributions to hgg coupling in warped extra dimensions (RS). We then apply similar techniques to calculate both KK fermion and KK gauge boson contributions to $h\gamma\gamma$ coupling. We show that simple analytical formulas can be obtained for these new physics contributions.

A. hgg coupling in RS

In this subsection, we consider the effect of the full KK fermion tower on hgg coupling. We consider models with bulk gauge group $SU(2)_L \otimes SU(2)_R$, which is motivated to ease the bound from electroweak precision test [7]. We consider here just a single family of quarks for

the sake of simplicity. A generalization to 3 generation quarks can be easily applied later. For the quark fields, we consider the simple spinorial representation with the following field contents:

$$\begin{pmatrix} Q_L^u(+,+), Q_R^u(-,-) \\ Q_L^d(+,+), Q_R^d(-,-) \end{pmatrix}, \quad \begin{pmatrix} U'_R(-,+), U'_L(+,-) \\ D_R(+,+), D_L(-,-) \end{pmatrix}, \quad \begin{pmatrix} U_R(+,+), U_L(-,-) \\ D'_R(-,+), D'_L(+,-) \end{pmatrix}. \quad (12)$$

The first multiplet is a doublet of $SU(2)_L$ and the last two are doublets of $SU(2)_R$. The boundary conditions are denoted for the corresponding chirality. They have the following Yukawa couplings ³

$$Y^u \sqrt{R} (\bar{Q}_L^u U_R + \bar{Q}_L^d D'_R) H + Y^d \sqrt{R} (\bar{Q}_L^u U'_R + \bar{Q}_L^d D_R) H + (L \leftrightarrow R) + \text{h.c.} \quad (13)$$

Note that Y^u, Y^d are dimensionless and order one, and $1/R = k$ is the curvature scale. After KK decomposition in the basis where Higgs vev is zero, we have zero modes $q_L^{u,(0)}, q_L^{d,(0)}, d_R^{(0)}, u_R^{(0)}$ and the KK modes $Q_{L,R}^{u,(i)}, Q_{L,R}^{d,(i)}, D_{L,R}^{(j)}, U_{L,R}^{(j)}, U'_{L,R}^{(k)}, D'_{L,R}^{(k)}$. For up-type quarks, we have the following infinite dimensional mass matrix

$$(\bar{q}_L^{u,(0)}, \bar{Q}_L^{u,(i)}, \bar{U}_L^{(j)}, \bar{U}'_L^{(k)}) \begin{pmatrix} \frac{Y_q^u \tilde{v}}{\sqrt{2}} & 0 & \frac{Y_{qU_b}^u \tilde{v}}{\sqrt{2}} & \frac{Y_{qU_c'}^d \tilde{v}}{\sqrt{2}} \\ \frac{Y_{Q_i u}^u \tilde{v}}{\sqrt{2}} & M_Q & \frac{Y_{Q_i U_b}^u \tilde{v}}{\sqrt{2}} & \frac{Y_{Q_i U_c'}^d \tilde{v}}{\sqrt{2}} \\ 0 & \frac{Y_{U_j Q_a}^{u,*} \tilde{v}}{\sqrt{2}} & M_U & 0 \\ 0 & \frac{Y_{U_k' Q_a}^{d,*} \tilde{v}}{\sqrt{2}} & 0 & M_{U'} \end{pmatrix} \begin{pmatrix} u_R^{(0)} \\ Q_R^{u,(a)} \\ U_R^{(b)} \\ U_R'^{(c)} \end{pmatrix} + \text{h.c.} \quad (14)$$

where i, j, k, a, b, c are KK indices. The Yukawa coupling matrices are defined e.g. by

$$Y_{Q_i U_b}^u = Y^u \sqrt{R} \int dz \left(\frac{R}{z} \right)^5 h(z) q_L^{u,(i)}(z) u_R^{(b)}(z), \quad (15)$$

i.e. it is an integral of product of Higgs and fermion wavefunctions, where $h(z)$ is a profile of the Higgs field normalized in the following way

$$1 = \int_R^{R'} dz \left(\frac{R}{z} \right)^3 h(z)^2. \quad (16)$$

The KK mass matrices are diagonal, e.g. $M_Q = \text{diag}(M_{Q_1}, M_{Q_2}, \dots)$. One naively might think that the couplings $Y_{U_j Q_a}$ vanish in the limit of brane Higgs due to the odd boundary conditions of U_L and Q_R^u , so it is safe to ignore them in this matrix. But these are precisely the Z_2 odd operators described in detail in [32] (detailed analysis without these operators

³ We consider here a general bulk Higgs [38] with vector-like Yukawa coupling for simplicity.

was presented in [13]). These operators as was shown in [32] lead to flavor violation in the Higgs sector, and they are also essential in evaluating the hgg coupling⁴. To avoid subtleties with wave function being discontinuous at IR brane we will assume that the Higgs is 5D bulk field and only at the end we will take a brane Higgs limit.

Now we can use the same determinant trick, the determinant of the mass matrix to the order of \tilde{v}^3 is

$$\begin{aligned} \text{Det}(\hat{M}) &= \left(\prod_{i,j,k} M_{Q_i} M_{U_j} M_{U'_k} \right) \times \\ &\left[\frac{Y_{qu}^u \tilde{v}}{\sqrt{2}} - Y_{qu}^u \left(\frac{\tilde{v}}{\sqrt{2}} \right)^3 \sum_{a,b} \left(\frac{Y_{Q_a U'_b}^d Y_{U'_b Q_a}^{d,*}}{M_{Q_a} M_{U'_b}} + \frac{Y_{Q_a U_b}^u Y_{U_b Q_a}^{u,*}}{M_{Q_a} M_{U_b}} \right) \right. \\ &\left. + \left(\frac{\tilde{v}}{\sqrt{2}} \right)^3 \sum_{a,b} \left(\frac{Y_{qU_b}^u Y_{U_b Q_a}^{u,*} Y_{Q_a u}^u}{M_{Q_a} M_{U_b}} + \frac{Y_{qU'_b}^d Y_{U'_b Q_a}^{d,*} Y_{Q_a u}^u}{M_{Q_a} M_{U'_b}} \right) \right]. \end{aligned} \quad (17)$$

Now we get

$$\begin{aligned} \text{Tr}(\hat{Y} \hat{M}^{-1}) &= \frac{\partial \ln \text{Det}(\hat{M})}{\partial \tilde{v}} = \frac{1}{\tilde{v}} \left[1 - \tilde{v}^2 \sum_{a,b} \left(\frac{Y_{Q_a U'_b}^d Y_{U'_b Q_a}^{d,*}}{M_{Q_a} M_{U'_b}} + \frac{Y_{Q_a U_b}^u Y_{U_b Q_a}^{u,*}}{M_{Q_a} M_{U_b}} \right) \right. \\ &\left. + \frac{\tilde{v}^2}{Y_{qu}^u} \sum_{a,b} \left(\frac{Y_{qU_b}^u Y_{U_b Q_a}^{u,*} Y_{Q_a u}^u}{M_{Q_a} M_{U_b}} + \frac{Y_{qU'_b}^d Y_{U'_b Q_a}^{d,*} Y_{Q_a u}^u}{M_{Q_a} M_{U'_b}} \right) \right]. \end{aligned} \quad (18)$$

Again, for the light generation quarks there are corrections to the SM fermion masses and Yukawa couplings [32]

$$\begin{aligned} m^{\text{light}} &= Y_{qu}^u \frac{\tilde{v}}{\sqrt{2}} + \sum_{a,b} Y_{qU_b}^u \frac{1}{M_{U_b}} Y_{U_b Q_a}^{u,*} \frac{1}{M_{Q_a}} Y_{Q_a u}^u \left(\frac{\tilde{v}}{\sqrt{2}} \right)^3 \\ &+ \sum_{a,b} Y_{qU'_b}^d \frac{1}{M_{U'_b}} Y_{U'_b Q_a}^{d,*} \frac{1}{M_{Q_a}} Y_{Q_a u}^u \left(\frac{\tilde{v}}{\sqrt{2}} \right)^3, \end{aligned} \quad (19)$$

$$\begin{aligned} y_{RS}^{\text{light}} &= \frac{Y_{qu}^u}{\sqrt{2}} + \frac{3}{\sqrt{2}} \sum_{a,b} Y_{qU_b}^u \frac{1}{M_{U_b}} Y_{U_b Q_a}^{u,*} \frac{1}{M_{Q_a}} Y_{Q_a u}^u \left(\frac{\tilde{v}}{\sqrt{2}} \right)^2 \\ &+ \frac{3}{\sqrt{2}} \sum_{a,b} Y_{qU'_b}^d \frac{1}{M_{U'_b}} Y_{U'_b Q_a}^{d,*} \frac{1}{M_{Q_a}} Y_{Q_a u}^u \left(\frac{\tilde{v}}{\sqrt{2}} \right)^2. \end{aligned} \quad (20)$$

Therefore

$$\frac{y_{RS}^{\text{light}}}{m^{\text{light}}} \approx \frac{1}{\tilde{v}} \left(1 + \sum_{a,b} Y_{Q_a u}^u Y_{U_b Q_a}^{u,*} Y_{qU_b}^u \tilde{v}^2 \frac{1}{M_{Q_a} M_{U_b} Y_{qu}^u} + \sum_{a,b} Y_{Q_a u}^u Y_{U'_b Q_a}^{d,*} Y_{qU'_b}^d \tilde{v}^2 \frac{1}{M_{Q_a} M_{U'_b} Y_{qu}^u} \right). \quad (21)$$

⁴ These operators can be mimicked by higher dimensional derivative operators [32], which shows UV sensitivity of the effect.

So the total contribution to hgg coupling by light generation quarks and their KK partners is (see Eq. 6)

$$-\tilde{v} \sum_{a,b} \left(\frac{Y_{Q_a U'_b}^d Y_{U'_b Q_a}^{d,*}}{M_{Q_a} M_{U'_b}} + \frac{Y_{Q_a U_b}^u Y_{U_b Q_a}^{u,*}}{M_{Q_a} M_{U_b}} \right) + \frac{y_{RS}^{\text{light}}}{m^{\text{light}}} A_{1/2}(\tau_{\text{light}}). \quad (22)$$

Note that this result is very similar to the one we obtained in the last section (Eq. 11), except for an extra term corresponding to the contribution of extra states in the doublet representation of $SU(2)_R$. For light generations, the last term is negligible, and we are left with first two terms. The first two terms can be written as

$$\begin{aligned} & -\tilde{v} \sum_{a,b} \left[Y^u Y^{u,*} R \left(\int dz dz' \left(\frac{R}{z} \right)^5 \left(\frac{R}{z'} \right)^5 \frac{q_L^{(a)}(z) q_R^{(a)}(z')}{M_{Q_a}} \frac{u_R^{(b)}(z) u_L^{(b)}(z')}{M_{U_b}} h(z) h(z') \right) \right. \\ & \left. + Y^d Y^{d,*} R \left(\int dz dz' \left(\frac{R}{z} \right)^5 \left(\frac{R}{z'} \right)^5 \frac{q_L^{(a)}(z) q_R^{(a)}(z')}{M_{Q_a}} \frac{u_R'^{(b)}(z) u_L'^{(b)}(z')}{M_{U'_b}} h(z) h(z') \right) \right]. \end{aligned} \quad (23)$$

Now we have to evaluate the following sums

$$\sum_{a>0} \frac{q_L^{(a)}(z) q_R^{(a)}(z')}{M_{Q_a}}, \quad \sum_{b>0} \frac{u_R^{(b)}(z) u_L^{(b)}(z')}{M_{U_b}}, \quad \sum_{b>0} \frac{u_R'^{(b)}(z) u_L'^{(b)}(z')}{M_{U'_b}}. \quad (24)$$

We can calculate them by using equations of motion for fermion wavefunctions (see discussion in the Appendix A). From the forms of these sums (see Eq. (A10)), we see that we need to evaluate the integrals of Higgs wavefunction times $\theta(z - z')$ and $\theta(z - z')^2$. This can be done for general bulk Higgs. But for illustration purpose we take the brane Higgs limit of bulk Higgs. Then we get

$$\int dz dz' \theta(z - z')^2 h^{\text{brane}}(z) h^{\text{brane}}(z') = \frac{1}{2}, \quad (25)$$

⁵ and Eq. (23) now reduces to

$$\frac{1}{2} (Y^u Y^{u,*} + Y^d Y^{d,*}) \tilde{v} R'^2. \quad (26)$$

Therefore, for light generations, the contribution to hgg coupling is $(Y^u Y^{u,*} + Y^d Y^{d,*}) \tilde{v} R'^2 / 2$, which comes just from KK fermions and is independent of fermion bulk mass parameters.

⁵ To evaluate this integral we have to somehow regularize the wavefunction of the brane Higgs(δ function), we used bulk Higgs inspired regularization of the delta function $h^{\text{brane}}(z) = \lim_{\beta \rightarrow \infty} \frac{\beta}{R'} \left(\frac{z}{R'} \right)^\beta$. One can also use a rectangular regularization of brane Higgs wavefunction which will lead to the same result.

For the third generation quarks there will be an extra contribution to the formula in (Eq. 21) which we parameterize following [32] as $(-\frac{\Delta_2^{t,b}}{m\tilde{v}})$ (see Appendix C for details). This gives us additional contribution relative to (Eq. 22)

$$\frac{\Delta_2^t}{m_t\tilde{v}} + \frac{\Delta_2^b}{m_b\tilde{v}}. \quad (27)$$

Also in this case contributions of the SM bottom and top quarks are no longer negligible, so we have to include them

$$\frac{y_b^{RS}}{m_b}A_{1/2}(\tau_b) + \frac{y_t^{RS}}{m_t}A_{1/2}(\tau_t). \quad (28)$$

Note that now Yukawa couplings of the top and bottom quarks are shifted(see discussion in Appendix C).

It is simple to generalize the above result to three generations. The KK towers of the quarks give a contribution proportional to $\text{Tr}(Y_u Y_u^\dagger + Y_d Y_d^\dagger)$, and we have to combine them with the effect coming from top and bottom quarks. To summarize, compared with SM, the Higgs production cross-section from gluon fusion in RS is

$$\frac{\sigma_{gg \rightarrow h}^{RS}}{\sigma_{gg \rightarrow h}^{SM}} = \left(\frac{v_{SM}}{\tilde{v}} \right)^2 \left| \frac{\text{Tr}(Y_u Y_u^\dagger + Y_d Y_d^\dagger)\tilde{v}^2 R'^2 + \frac{\Delta_2^t}{m_t} + \frac{\Delta_2^b}{m_b} + x_t A_{1/2}(\tau_t) + x_b A_{1/2}(\tau_b)}{A_{1/2}(\tau_t) + A_{1/2}(\tau_b)} \right|^2, \quad (29)$$

where $x_t = \frac{y_t^{RS}\tilde{v}}{m_t}$ and $x_b = \frac{y_b^{RS}\tilde{v}}{m_b}$, with y_t^{RS}, y_b^{RS} the shifted top and bottom Yukawa couplings in RS (reference [12] presented numerical results for the analysis of the brane Higgs model including Z_2 odd operators, however, it is hard to compare it with our result due to different particle content of the models). We consider here the ratio $\frac{\sigma_{gg \rightarrow h}^{RS}}{\sigma_{gg \rightarrow h}^{SM}}$ in order to reduce the uncertainty coming from higher order QCD corrections. It is also important to notice that in the case when the couplings of the $SU(2)_L$ and $SU(2)_R$ are not equal the ratio $(\frac{v_{SM}}{\tilde{v}})$ might be quite significant, see discussion and analysis in [13]. In the rest of the paper we will assume that $SU(2)_L$ and custodial $SU(2)_R$ have the same gauge couplings (see appendix B for discussion of VEV shift in this case).

It is also interesting to point out that the same diagrams that contribute to the gluon fusion will also contribute to the modification of the di-Higgs production. This might become an interesting option to disentangle new physics contribution (see discussion in the effective field theory approach in [35]).

B. $h\gamma\gamma$ coupling in RS

The calculation of the $h\gamma\gamma$ coupling comes from similar diagrams as the one for the hgg coupling, the only difference now is that we have to take into account contributions of the towers of charged KK gauge bosons and KK leptons. We will again use the simplest custodial model where leptons are in the doublet representation of $SU(2)_L$ or $SU(2)_R$. We can calculate their contribution in the same way as we did for the quarks. Contribution of the KK tower of the W_{\pm} was presented in [13], so here we just quote their results and the reader can find more details about the derivation in the Appendix B. The contribution of the tower of the KK W_{\pm} is given by

$$\sum_{n \geq 0} \frac{C_{diag}^n}{2M_n^2} A_1(\tau_n) = \frac{C_{hww}}{2M_w^2} (A_1(\tau_w) + 7) - \frac{7}{\tilde{v}}, \quad (30)$$

where C_{diag}^n is coupling between Higgs field and the n-th KK modes (mass eigenstates) of the W_{\pm} , and C_{hww} is coupling between SM W and the Higgs. $A_1(\tau_w)$ is the form-factor for the gauge bosons (see Eq. (B7)). Including the modification of the coupling between SM W and Higgs, this sum can be expresssed in the following way:

$$\begin{aligned} \sum_{n \geq 0} \frac{C_{diag}^n}{2M_n^2} A_1(\tau_n) &= \frac{g^2 \tilde{v}}{4M_w^2} \left(1 - \frac{\tilde{v}^2 R'^2 (g_{5D}^2 + \tilde{g}_{5D}^2)}{4R} \right) (A_1(\tau_w) + 7) - \frac{7}{\tilde{v}} \\ &\approx \frac{1}{\tilde{v}} \left[\left(1 - \frac{\tilde{v}^2 R'^2 (g_{5D}^2 + \tilde{g}_{5D}^2)}{8R} \right) A_1(\tau_w) - \frac{7}{8} \tilde{v}^2 R'^2 \frac{(g_{5D}^2 + \tilde{g}_{5D}^2)}{R} \right], \end{aligned} \quad (31)$$

where g_{5D} and \tilde{g}_{5D} are the 5D gauge couplings of $SU(2)_L$ and $SU(2)_R$ respectively. Adding both fermion and gauge boson contributions together, now we can present our results for the ratio of $\Gamma(h \rightarrow \gamma\gamma)$ between RS and SM:

$$\begin{aligned} \frac{\Gamma^{RS}(h \rightarrow \gamma\gamma)}{\Gamma^{SM}(h \rightarrow \gamma\gamma)} &= \left(\frac{v_{SM}}{\tilde{v}} \right)^2 \frac{1}{|A_1(\tau_w) + \frac{16}{9} A_{1/2}(\tau_t) + \frac{4}{9} A_{1/2}(\tau_b)|^2} \\ &\left| \left(1 - \frac{v_{SM}^2 R'^2 (g_{5D}^2 + \tilde{g}_{5D}^2)}{8R} \right) A_1(\tau_w) - \frac{7v_{SM}^2 R'^2 (g_{5D}^2 + \tilde{g}_{5D}^2)}{8R} + \frac{16}{9} x_t A_{1/2}(\tau_t) \right. \\ &\quad \left. + \frac{4}{9} x_b A_{1/2}(\tau_b) + \frac{1}{2} v_{SM}^2 R'^2 \text{Tr} \left[\frac{20}{9} \left(Y_u^\dagger Y_u + Y_d^\dagger Y_d \right) + \frac{4}{3} Y_l^\dagger Y_l \right] + \frac{16\Delta_2^t}{9m_t} + \frac{4\Delta_2^b}{9m_b} \right|^2. \end{aligned} \quad (32)$$

IV. PHENOMENOLOGY

In this section, we discuss the phenomenology of the Higgs boson in warped extra dimensions. We focus our study on the Higgs production through gluon fusion and the branching

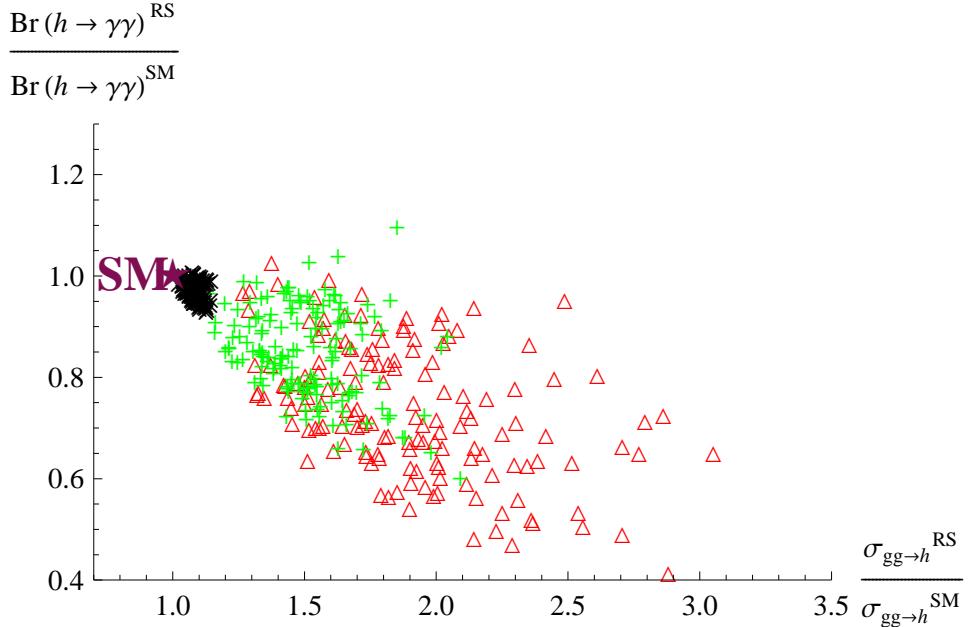


FIG. 2: Scattered plot of $\frac{\sigma_{gg \rightarrow h}^{RS}}{\sigma_{gg \rightarrow h}^{SM}}$ and $\frac{\text{Br}(h \rightarrow \gamma\gamma)^{RS}}{\text{Br}(h \rightarrow \gamma\gamma)^{SM}}$, for bulk Higgs with vector-like Yukawa couplings ($Y_1 = Y_2$). The dimensionless 5D Yukawa couplings are varied between $Y \in [0.3, 3]$ and $m_h = 120$ GeV. The black “ \times ” corresponds to the KK scale $R'^{-1} = 5$ TeV, green “ $+$ ” to $R'^{-1} = 2$ TeV, and red “ \triangle ” to $R'^{-1} = 1.5$ TeV. The SM value is marked by the star.

fraction of $h \rightarrow \gamma\gamma$ decay. We will compare our results with that of holographic PNGB Higgs model studied in [15].

To get a handle on the size of new physics contributions, we scan the parameter space of RS with the assumption of flavor anarchy, i.e. the 5D Yukawa matrices are order one and uncorrelated. We find the set of 5D Yukawa couplings and fermion zero mode wavefunctions which give the correct SM quark masses and CKM mixing. We then calculate $\sigma(gg \rightarrow h)$ and $\text{Br}(h \rightarrow \gamma\gamma)$ using Eq. (29) and (32), and find the ratio with that of SM. The result of the scan for bulk Higgs is shown in Fig. 2.

We can see from the plot in Fig. 2 that the new physics contribution to $\sigma(gg \rightarrow h)$ tends to be positive and gets larger for lower KK scale. Also the new physics contribution to $\sigma(gg \rightarrow h)$ and $\text{Br}(h \rightarrow \gamma\gamma)$ are correlated: an increase in $\sigma(gg \rightarrow h)$ is accompanied by a decrease in $\text{Br}(h \rightarrow \gamma\gamma)$. Before proceeding further let us stop and see whether we can understand these results intuitively. First let us focus on the enhancement of the Higgs production due to gluon fusion. As we argued in the sections III A these effects come mainly from the modification of the top Yukawa coupling and from the loop with KK fermions. As was shown in [32] top Yukawa coupling is reduced compared to the SM value, so naively one

should expect the reduction of the Higgs production. But let us now look on the contribution of the KK modes. One can see from (Eq. 29) that this contribution is proportional to $\text{Tr}(Y_u Y_u^\dagger + Y_d Y_d^\dagger)$ which is always positive, so the sign of this contribution is fixed. Also the typical size of this term will be roughly equal to $N^2 \bar{Y}^2$ where N is number of SM families and \bar{Y} is an average size of the Yukawa couplings, so adding both up and down quark KK towers will lead to an overall enhancement factor of 18.⁶ Therefore KK fermions give a large positive contribution to $\sigma(gg \rightarrow h)$. Reduction of the $\text{Br}(h \rightarrow \gamma\gamma)$ can be understood from the fact that in the SM the dominant contribution comes from the loop with W^\pm , and the fermion contribution has an opposite sign, thus enhancement of the fermion contributions effectively decreases the overall coupling.

This implication is two-fold. First, it means that even with a KK scale out of the reach of the LHC ($\gtrsim 5$ TeV), we can still probe the framework of warped extra dimension by precision measurements of various Higgs production and decay processes. Second, by comparing our result with that of [15], we can see that $\sigma(gg \rightarrow h)$ can be used to distinguish between RS with bulk Higgs and holographic PNGB Higgs model (or gauge-Higgs unification). In the latter model, a reduction is usually expected, which can be contrasted with our results for bulk Higgs. Note that the difference in these two models comes from the extra symmetry in PNGB Higgs, which constrains the Higgs interactions (see discussion in [16, 17]).

To study the dependence of new physics contributions on the Higgs boson mass, we plot in Fig. 3 the ratio $\frac{\sigma_{gg \rightarrow h}^{RS}}{\sigma_{gg \rightarrow h}^{SM}}$ vs. m_h for various KK scales. We can see that the new physics contribution decreases as m_h increase from 100 to ~ 360 GeV. This can be understood from the fact that in SM, the form factor for the top quark attains its largest value when $m_h \approx 2m_t$. Since in RS with bulk Higgs, the top quark Yukawa coupling is reduced compared to that of SM, there is a larger negative new physics contribution to hgg coupling when $m_h \approx 2m_t$, leading to a smaller total new physics contribution.

In Fig. 4, we plot the dependence of the ratio $\frac{\sigma_{gg \rightarrow h}^{RS}}{\sigma_{gg \rightarrow h}^{SM}}$ on the average size of the 5D Yukawa couplings. We can see quite clearly that the size of new physics contribution increases as the 5D Yukawa couplings increases. This is expected from the fact that KK fermion contributions are proportional to $\text{Tr}(Y_u Y_u^\dagger + Y_d Y_d^\dagger)$. In the framework of flavor anarchy, the

⁶ One can see that for sufficiently large Yukawa couplings our expansion in powers of $YY^\dagger v^2 R^2$ might become ill defined, and also contribution of the higher order loops with KK fermions and Higgs might become important, so the one loop result becomes not reliable if the new physics contribution is much larger than that of the SM. At the same time we would like to note that our result even for the large 5D Yukawa couplings will give a typical size of the expected correction to the SM coupling.

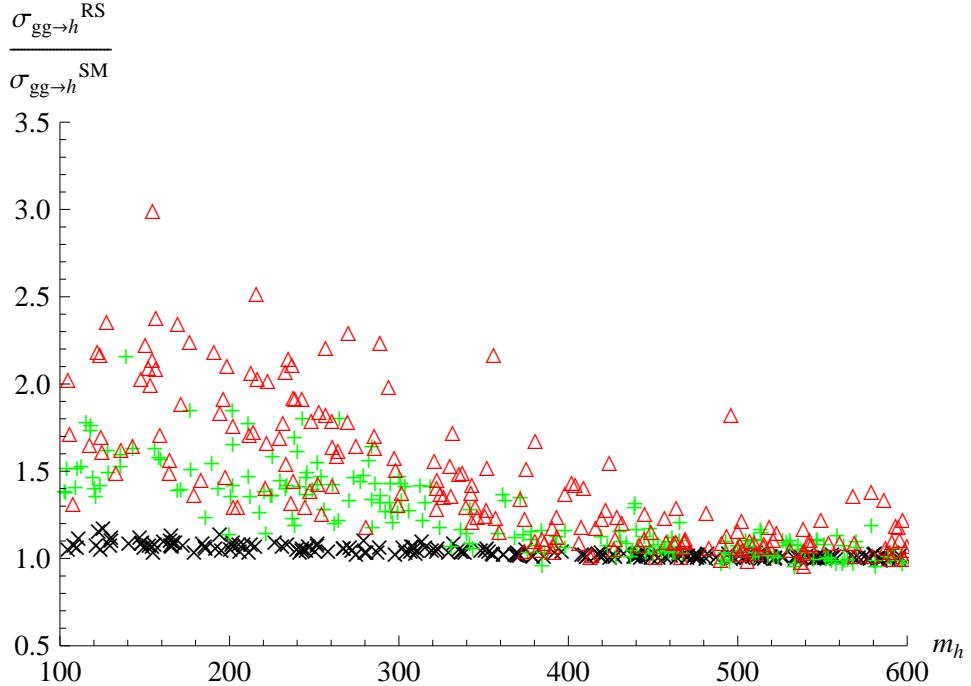


FIG. 3: Dependence of $\frac{\sigma_{gg \rightarrow h}^{RS}}{\sigma_{gg \rightarrow h}^{SM}}$ on the Higgs mass for different values of R'^{-1} in bulk Higgs scenario with vector-like Yukawa couplings ($Y_1 = Y_2$). The dimensionless 5D Yukawa couplings are varied between $Y \in [0.3, 3]$. The black “ \times ” corresponds to KK scale $R'^{-1} = 5$ TeV, green “ $+$ ” to $R'^{-1} = 2$ TeV, and red “ \triangle ” to $R'^{-1} = 1.5$ TeV.

5D Yukawa couplings are order one. We can see from Fig. 4 that for order one Yukawa couplings, we have sizable new physics contributions to $\sigma(gg \rightarrow h)$.

So far we have been assuming that the Higgs is the bulk field and 5D Yukawa couplings are vector-like i.e.

$$\mathcal{L} = Y_1 \bar{Q}_L^u U_R H + Y_2 \bar{U}_L Q_R^u H \quad \text{with } Y_1 = Y_2. \quad (33)$$

In the case where the Higgs is a 5D bulk field this condition of $Y_1 = Y_2$ is forced by the 5D Lorentz symmetry. But the Higgs can be brane localized or even a bulk Higgs might have brane localized couplings and these couplings do not have to respect 5D bulk Lorentz symmetry. So generally speaking $Y_1 \neq Y_2$, and they could be independent of each other. Let us see how this might modify our results. The first thing to notice is that the contribution of the tower of KK modes now has the following structure $Y_1 Y_2^\dagger$. Before proceeding further we immediately see that the overall sign of the contribution is not fixed any more! So we cannot predict in generic RS model the sign of the effect: whether it is enhancement or suppression for both hgg and $h\gamma\gamma$ couplings. This is shown in Fig. 5. We can see that the

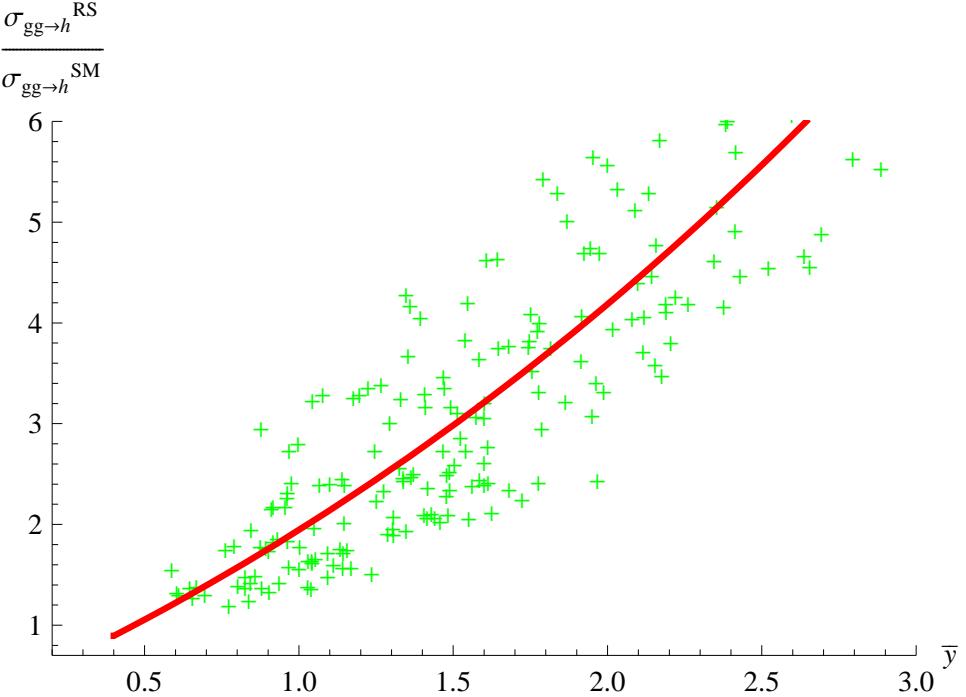


FIG. 4: Dependence of $\frac{\sigma_{gg \rightarrow h}^{RS}}{\sigma_{gg \rightarrow h}^{SM}}$ on the average size of dimensionless 5D Yukawa couplings \bar{Y} , for the Higgs mass $m_h = 120$ GeV and KK scale $R'^{-1} = 2$ TeV.

size of new physics contribution is generically large for moderate KK scale, but now its sign can be both positive and negative.

V. CONCLUSIONS

In conclusion, we summarize the results presented in the paper. We calculated the corrections to the hgg and $h\gamma\gamma$ couplings in RS at one loop order. We have found that the new physics states can modify significantly these couplings. We have shown that the dominant contribution to these coupling comes from the towers of KK fermions running inside triangle diagrams. We have shown that the KK towers of the light fermions do contribute significantly to these couplings, contrary to the models with Higgs being a PNGB boson where this contribution is sub-leading. We have shown that in the models with the Higgs in the bulk and Yukawa couplings being vectorlike ($Y_1 = Y_2$), hgg coupling becomes enhanced and $h\gamma\gamma$ coupling suppressed compared to that of SM, even though the top Yukawa coupling is suppressed compared to the SM value. This naively counterintuitive result is explained by the fact that the contribution of the KK towers of all SM fermions is so strong that it overcomes the effect from suppression of the top Yukawa coupling. Modification of the Higgs

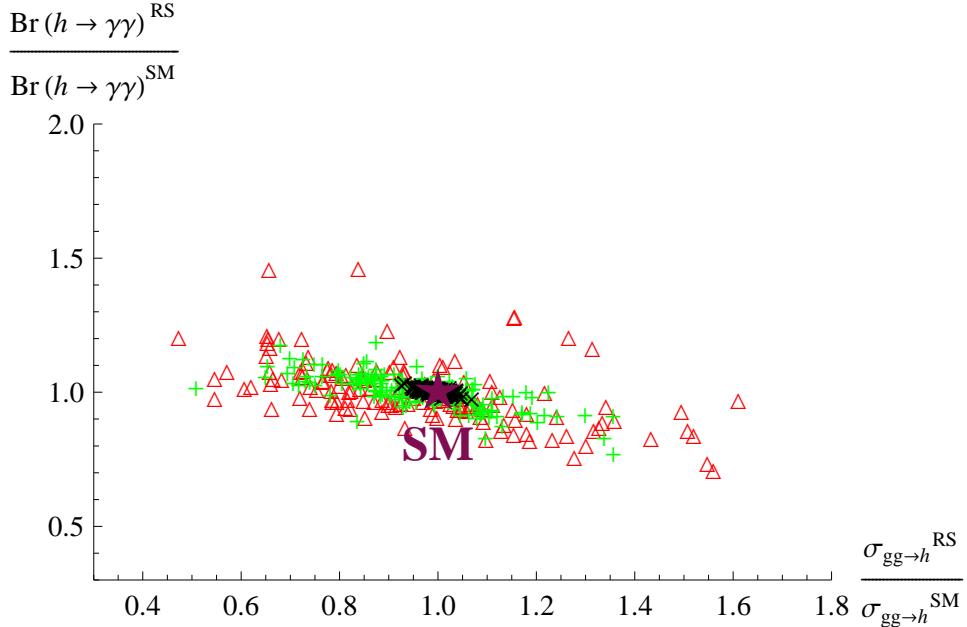


FIG. 5: Scattered plot for the modification of $\frac{\text{Br}(h \rightarrow \gamma\gamma)^{\text{RS}}}{\text{Br}(h \rightarrow \gamma\gamma)^{\text{SM}}}$ and $\frac{\sigma_{gg \rightarrow h}^{\text{RS}}}{\sigma_{gg \rightarrow h}^{\text{SM}}}$ for brane Higgs with Y_1 independent of Y_2 , where 5D Yukawa couplings are varied between $Y \in [0.3, 3]$ and $m_h = 120$ GeV. The black “ \times ” corresponds to the KK scale $R'^{-1} = 5$ TeV, green “ $+$ ” to the $R'^{-1} = 2$ TeV, and red “ Δ ” to the $R'^{-1} = 1.5$ TeV. The SM value is marked by the star.

production cross-section remains significant even for a KK scale far from LHC accessibility. Specifically, we can get order one corrections even with lightest KK modes above 5 TeV. For the generic models with Higgs on the brane or bulk Higgs with brane Yukawa couplings the sign of the effect remains unpredictable. We might have enhancement as well as suppression, but the parametric size of the effect remains the same. The total effect comes from collective contributions of the KK partners of all generations. Therefore, the size of these new physics contributions is large, even if the KK fermions are heavy. This shows us that in the absence of new resonances an analysis of the Higgs couplings might become a very important tool in understanding the structure of BSM physics.

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Appendix A: KK sum rules

In this section we will present a way of efficiently performing KK sums for the fermions⁷ (such as Eq. (24)). Let us look at the equations of motions for the fermions in the absence of the Higgs vev. In the absence of the Higgs vev we can always choose a basis where 5D bulk masses are diagonal, and so we can ignore all the mixings. Let us concentrate on the KK decomposition of the $SU(2)_L$ doublet $Q_{L,R}$ with boundary conditions (\pm, \pm) . The equations of motion of the KK wavefunctions are

$$-m_n q_L^{(n)} - \partial_z q_R^{(n)} + \frac{c_q + 2}{z} q_R^{(n)} = 0, \quad (\text{A1})$$

$$-m_n^* q_R^{(n)} + \partial_z q_L^{(n)} + \frac{c_q - 2}{z} q_L^{(n)} = 0. \quad (\text{A2})$$

⁷ Similar tricks were discussed in [39]

We take the first equation and rewrite it as:

$$-m_n q_L^{(n)} - z^{c_q+2} \partial_z \left(q_R^{(n)} z^{-c_q-2} \right) = 0. \quad (\text{A3})$$

We now multiply by z^{-c_q-2} and integrate between R and z_1 :

$$\begin{aligned} -m_n \int_R^{z_1} dz z^{-c_q-2} q_L^{(n)}(z) &= q_R^{(n)} z^{-c_q-2} \Big|_R^{z_1}, \\ \int_R^{z_1} dz z^{-c_q-2} q_L^{(n)}(z) &= -\frac{1}{m_n} q_R^{(n)}(z_1) z_1^{-c_q-2}. \end{aligned} \quad (\text{A4})$$

We now use the completeness relation

$$\sum_{n=0}^{\infty} q_L^{(n)}(z_2) q_L^{(n)}(z) = \frac{z^4}{R^4} \delta(z_2 - z) \quad (\text{A5})$$

$$\Rightarrow \sum_{n=1}^{\infty} q_L^{(n)}(z_2) q_L^{(n)}(z) = \frac{z^4}{R^4} \delta(z_2 - z) - q_L^0(z_2) q_L^0(z). \quad (\text{A6})$$

Based on (Eq A4) we will get

$$-\int_R^{z_1} dz z^{-c_q-2} \sum_{n=1}^{\infty} q_L^{(n)}(z_2) q_L^{(n)}(z) = z_1^{-c_q-2} \sum_{n=1}^{\infty} \frac{q_R^{(n)}(z_1) q_L^{(n)}(z_2)}{m_n}, \quad (\text{A7})$$

where we have explicitly extracted the zero mode contribution from the sum. Let us note that

$$q_L^0(z) = N_L z^{2-c_q} \quad \text{with} \quad N_L = \sqrt{\frac{1-2c_q}{\epsilon^{2c_q-1}-1}} R^{c_q-5/2}, \quad (\text{A8})$$

and where we have defined the warp factor $\epsilon = \frac{R}{R'} \sim 10^{-16}$.

Now we can finally write:

$$\begin{aligned} \sum_{n=1}^{\infty} \frac{q_R^{(n)}(z_1) q_L^{(n)}(z_2)}{m_n} &= -z_1^{c_q+2} \int_R^{z_1} dz z^{-c_q-2} \left(\frac{z^4}{R^4} \delta(z_2 - z) - q_L^0(z_2) q_L^0(z) \right) \\ &= \frac{z_1^{2+c_q} z_2^{2-c_q}}{R^4} \left[-\theta(z_1 - z_2) + \frac{\left(\frac{z_1}{R}\right)^{1-2c} - 1}{\left(\frac{R'}{R}\right)^{1-2c} - 1} \right]. \end{aligned} \quad (\text{A9})$$

Similarly we can calculate the sum for the other three possible boundary conditions :

$$\begin{aligned} \psi_L(+,+) : \quad \sum \frac{q_R^{(n)}(z_1) q_L^{(n)}(z_2)}{m_n} &= \frac{z_1^{2+c_q} z_2^{2-c_q}}{R^4} \left[-\theta(z_1 - z_2) + \frac{\left(\frac{z_1}{R}\right)^{1-2c} - 1}{\left(\frac{R'}{R}\right)^{1-2c} - 1} \right], \\ \psi_L(+,-) : \quad \sum \frac{q_R^{(n)}(z_1) q_L^{(n)}(z_2)}{m_n} &= -\frac{z_1^{2+c_q} z_2^{2-c_q}}{R^4} \theta(z_1 - z_2), \\ \psi_L(-,+) : \quad \sum \frac{q_R^{(n)}(z_1) q_L^{(n)}(z_2)}{m_n} &= \frac{z_1^{2+c_q} z_2^{2-c_q}}{R^4} \theta(z_2 - z_1), \\ \psi_L(-,-) : \quad \sum \frac{q_R^{(n)}(z_1) q_L^{(n)}(z_2)}{m_n} &= \frac{z_1^{2+c_q} z_2^{2-c_q}}{R^4} \left[\theta(z_2 - z_1) - \frac{\left(\frac{z_2}{R}\right)^{1+2c} - 1}{\left(\frac{R'}{R}\right)^{1+2c} - 1} \right]. \end{aligned} \quad (\text{A10})$$

Using these relations we can now perform all the necessary sums to calculate the KK fermion contribution to hgg coupling.

Appendix B: Gauge boson couplings and contribution to $h\gamma\gamma$ coupling

In this section just for the sake of the completion we present analysis for the modification of the gauge boson coupling to the Higgs boson, and their contribution to the $h\gamma\gamma$ coupling. We start from the modification of the Higgs vev

$$v_{SM}^2 \approx \tilde{v}^2 - \frac{\tilde{v}^4 R'^2}{8R} (g_{5D}^2 + \tilde{g}_{5D}^2), \quad (\text{B1})$$

where $v_{SM} = 246$ GeV, \tilde{g}_{5D} is five dimensional gauge coupling of the custodial $SU(2)_R$, so

$$\tilde{v} \approx v_{SM} \left(1 + \frac{R'^2 v_{SM}^2}{16R} (g_{5D}^2 + \tilde{g}_{5D}^2) \right). \quad (\text{B2})$$

This effect will lead to the overall modification of the SM hgg and $h\gamma\gamma$ coupling by the factor $1 - \frac{R'^2 v_{SM}^2}{16R} (g_{5D}^2 + \tilde{g}_{5D}^2) \approx 0.95$ for ($R'^{-1} = 1500$ TeV, $g_{5D} = \tilde{g}_{5D}$).

1. Couplings of W^\pm to Higgs in RS

To calculate modification of the $h\gamma\gamma$ coupling we also have to calculate contribution coming from the W boson. From the Lagrangian (see [7])

$$\mathcal{L} = \frac{g^2}{2} \left(\left(\frac{h + \tilde{v}}{\sqrt{2}} \right)^2 - \frac{R'^2 (g_{5D}^2 + \tilde{g}_{5D}^2)}{4R} \left(\frac{h + \tilde{v}}{\sqrt{2}} \right)^4 \right) W_\mu^+ W^{-\mu}, \quad (\text{B3})$$

one can immediately deduce coupling between Higgs and W .

$$\begin{aligned} \mathcal{L} &= C_{hww} h W_\mu^+ W^{-\mu}, \\ C_{hww} &= \frac{g^2 \tilde{v}}{2} \left[1 - \frac{R'^2 (g_{5D}^2 + \tilde{g}_{5D}^2) \tilde{v}^2}{4R} \right]. \end{aligned} \quad (\text{B4})$$

2. Contribution of the KK tower of W_\pm to the $h\gamma\gamma$

In this subsection we derive the contribution of the W_\pm KK modes to the $h\gamma\gamma$ coupling (we will closely follow discussion presented in [13]). First let us denote by M^2 the mass squared matrix of the charged gauge bosons, then the coupling to the Higgs boson will be given by the matrix

$$C = \frac{\partial M^2}{\partial \tilde{v}},$$

rotating back to the basis where mass matrix M^2 is diagonal we will get

$$C_{diag} = U \frac{\partial M^2}{\partial \tilde{v}} U^\dagger, \quad (\text{B5})$$

where U is a unitary matrix that diagonalizes M . We can parameterize the contribution of the gauge boson KK modes to the $h\gamma\gamma$ coupling in the following way:

$$\sum_{n \geq 0} \frac{C_{diag}^n}{2M_n^2} A_1(\tau_n) = \frac{C_{hww}}{2M_w^2} A_1(\tau_w) + \sum_{n > 0} \frac{C_{diag}^n}{2M_n^2} A_1(\tau_n), \quad (\text{B6})$$

where $A_1(\tau)$ is the form factor for vector bosons in the loop [36] ($\tau = m_h^2/4M_n^2$)

$$A_1(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]\tau^{-2}, \quad (\text{B7})$$

where $f(\tau)$ is given by Eq. (3). For KK gauge bosons $\tau_n \rightarrow 0$, and $A_1(\tau_n) \approx -7$, so we get

$$\frac{C_{hww}}{2M_w^2} A_1(\tau_w) - 7 \sum_{n > 0} \frac{C_{diag}^n}{2M_n^2} = \frac{C_{hww}}{2M_w^2} (A_1(\tau_w) + 7) - 7 \sum_{n \geq 0} \frac{C_{diag}^n}{2M_n^2}. \quad (\text{B8})$$

To evaluate $\sum_{n \geq 0} \frac{C_{diag}^n}{2M_n^2}$ we can use the following trick [37]

$$\sum_{n \geq 0} \frac{C_{diag}^n}{M_n^2} = \text{Tr} \left[(M_{diag}^2)^{-1} C \right] = \text{Tr} \left[\frac{\partial M^2}{\partial \tilde{v}} (M^2)^{-1} \right] = \frac{\partial}{\partial \tilde{v}} \ln (\text{Det} M^2). \quad (\text{B9})$$

Let us see how the determinant of the gauge boson mass matrix depends on \tilde{v} . For simplicity we assume that the Higgs is localized on the IR brane. We denote by $f_{(i)}, \tilde{f}_{(j)}$ values of the profiles on the IR brane for KK modes of $SU(2)_L$ and $SU(2)_R$ gauge bosons respectively. Then the mass matrix will look like:

$$M^2 = \begin{pmatrix} g_{5D}^2 f_{(0)}^2 \frac{\tilde{v}^2}{4} & f_{(0)} f_{(1)} g_{5D}^2 \frac{\tilde{v}^2}{4} & f_{(0)} \tilde{f}_{(1)} g_{5D} \tilde{g}_{5D} \frac{\tilde{v}^4}{2} & \dots \\ g_{5D}^2 f_{(0)} f_{(1)} \frac{\tilde{v}^2}{4} & M_1^2 + f_{(1)}^2 g_{5D}^2 \frac{\tilde{v}^2}{4} & f_{(1)} \tilde{f}_{(1)} g_{5D} \tilde{g}_{5D} \frac{\tilde{v}^2}{4} & \dots \\ g_{5D} \tilde{g}_{5D} f_{(0)} \tilde{f}_{(1)} \frac{\tilde{v}^2}{4} & f_{(1)} \tilde{f}_{(1)} g_{5D} \tilde{g}_{5D} \frac{\tilde{v}^2}{4} & \tilde{M}_1^2 + \tilde{f}_{(1)}^2 \tilde{g}_{5D}^2 \frac{\tilde{v}^2}{4} & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}. \quad (\text{B10})$$

One can see from the structure of the matrix that the determinant is equal to

$$\text{Det} M^2 = g_{5D}^2 f_{(0)}^2 \frac{\tilde{v}^2}{4} \prod_{i,j} M_i^2 \tilde{M}_j^2. \quad (\text{B11})$$

We have checked that for generic bulk Higgs $\text{Det} M^2 \propto \tilde{v}^2 + O(\tilde{v}^6)$, one can calculate it using mixed position momentum propagators. So the results presented in this section are approximately independent of the Higgs localization. Now we can proceed to the evaluation of the sum in Eq. (B8) and substituting result for the determinant we get

$$\sum_{n \geq 0} \frac{C_{diag}^n}{2M_n^2} A_1(\tau_n) = \frac{C_{hww}}{2M_w^2} (A_1(\tau_w) + 7) - \frac{7}{\tilde{v}}. \quad (\text{B12})$$

Appendix C: Review of Higgs Flavor violation

In this appendix we present general formulas for the misalignment between SM fermion masses and Higgs Yukawa couplings in RS(see for details[32]). We define the following quantity to parameterize the misalignment

$$\hat{\Delta} = \hat{m} - \tilde{v}\hat{y}, \quad (\text{C1})$$

where \hat{m}, \hat{y} are mass matrix and Yukawa couplings of the SM fermions. Then it can be split into two parts

$$\hat{\Delta} = \hat{\Delta}_1 + \hat{\Delta}_2, \quad (\text{C2})$$

where $\hat{\Delta}_1$ is the main contribution for the light generations and $\hat{\Delta}_2$ becomes important only for the third generation of quarks. Then calculations show that $\hat{\Delta}_1$ for the up type quarks is equal to

$$\hat{\Delta}_1^u = \frac{\tilde{v}\sqrt{2}}{3} \left(\frac{\tilde{v}^2 R'^2}{2} \right) \hat{F}(c_q) \left[Y_u Y_u^\dagger Y_u + Y_d Y_d^\dagger Y_u \right] \hat{F}(-c_u) \quad (\text{C3})$$

⁸ where c_u, c_q are bulk mass parameters for the multiplets containing zero modes of the SM right-handed and left-handed up quarks respectively. $\hat{F}(c)$ is a diagonal matrix with elements given by the profiles of the corresponding quarks respectively

$$F(c) \equiv \sqrt{\frac{1-2c}{1-\left(\frac{R}{R'}\right)^{1-2c}}}. \quad (\text{C4})$$

One can get these expressions by evaluating the sum (Eq. 19) directly using the rules of (Eq. A10) or by solving for the exact wavefunctions profiles as described in [32]. For the other contribution $\hat{\Delta}_2$ we will get the following expression

$$\hat{\Delta}_2^u = R'^2 \left[\hat{m}_u^\dagger \hat{K}(c_q) + \hat{K}(-c_u) \hat{m}_u^\dagger \right] m_u + \hat{m}_d \hat{\tilde{K}}(-c_d) \hat{m}_d^\dagger \hat{m}_u \quad (\text{C5})$$

where

$$\begin{aligned} \tilde{K}(c) &\equiv \frac{1-\left(\frac{R'}{R}\right)^{2c-1}}{1-2c} \frac{1-\left(\frac{R'}{R}\right)^{-2c-1}}{1+2c}, \\ K(c) &\equiv \frac{1}{1-2c} \left[-\frac{1}{\left(\frac{R}{R'}\right)^{2c-1}-1} + \frac{\left(\frac{R}{R'}\right)^{2c-1}-\left(\frac{R}{R'}\right)^2}{\left(\left(\frac{R}{R'}\right)^{2c-1}-1\right)(3-2c)} + \frac{\left(\frac{R}{R'}\right)^{1-2c}-\left(\frac{R}{R'}\right)^2}{(1+2c)\left(\left(\frac{R}{R'}\right)^{2c-1}-1\right)} \right] \end{aligned} \quad (\text{C6})$$

Note that subdominant contribution Δ_2 is only important for the third generation, and in the text we denote $\Delta_2^{t,b}$ to be equal to $(\hat{\Delta}_2^{u,d})_{33}$.

⁸ We assume here that Yukawa couplings are vectorlike $Y_2 = Y_1$